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Extrapolation of damage test data to predict performance of large-area NIF optics at 355 nm*

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ABSTRACT

For the aggressive fluence requirements of the NIF laser, some level of laser-induced damage to the large (40x40 cm) 351 nm final optics is inevitable. Planning and utilization of NIF therefore requires reliable prediction of the functional degradation of the final optics.

Laser damage tests are typically carried out with Gaussian beams on relatively small test areas. The tests yield a damage probability vs. energy fluence relation. These damage probabilities are shown to depend on both the beam fluence distribution and the size of area tested. Thus, some analysis is necessary in order to use these test results to determine expected damage levels for large aperture optics.

We present a statistical approach which interprets the damage probability in terms of an underlying intrinsic surface density of damaging defects. This allows extrapolation of test results to different sized areas and different beam shapes (NIF has a flattop beam). The defect density is found to vary as a power of the fluence (Weibull distribution).

Keywords: laser initiated damage, statistics, large optics

2. INTRODUCTION

Laser damage testing at LLNL serves at least two purposes. First, testing is used as an indicator of damage resistance of optical elements prepared by different processes and for assurance that processing parameters have not changed. Secondly, and more challenging, we want to use the results of laboratory laser damage testing to predict the operational performance of such optics with respect to laser induced damage. This later function is especially important since the "first bundle" (8 beams) of NIF will not come on line for about 18 months, and Livermore no longer has the Beamlet laser available for large aperture testing. In the meantime, only relatively small aperture damage testing will be available. Typical damage testing is done with small Gaussian beams ($1/e^2$ diameter ~ 1 mm) and relatively small test areas (few cm^2). For the large areas in NIF (192 beams with final optics 40x40 cm), the issue is not whether or not there will be damage. Damage is certain. The relevant question is the concentration of damage and the extent to which it impacts the functional role of a particular optic. The present paper presents a conceptual viewpoint from which to address both scaling from laboratory scale to large scale optics and part of the basis for the prediction of optical lifetimes. Several other papers in these proceedings describe LLNL's related efforts to optimize laser damage testing and interpretation of test results. These papers include detailed descriptions of testing of fused silica (Schwartz, et al), KDP (Runkel, et al), damage growth in coatings (Maricle, et al) and silica (Salleo, et al) and full aperture system tests (Kozlowski, et al).

Laser induced surface damage initiates at extrinsic defects which affect the near-surface transparency. Qualitatively, this statement is supported by the probabilistic nature of observed damage thresholds and the increased variance of observed thresholds with decrease of the illuminated area. The specific nature of responsible defects doubtless depends on the type of material (glass, fused silica, KDP), polishing procedure, radiation wavelength, etc. In order to estimate operational damage probabilities for large optics from experimental results with smaller optics, it is useful to apply a well founded phenomenological approach involving a few empirical parameters to do the extrapolation. This is the first step in developing a general laser damage reliability model for large optics.

Our problem is a special case of the general need to predict the reliability of a system subject to failure at its weakest points, a problem which has been of great importance to industry[1]. Specific examples of relevance concern the mechanical strength of optical fibers[2] and the electrical breakdown of insulation on coaxial electrical cables[3]. In both of these cases, one wishes to estimate the behavior of very long cables from tests conducted on much shorter lengths. A similar approach was used in a 1970's Arzamas study[4] of area dependence of laser glass damage thresholds. An initial statistical description of laser damage initiation was given in ref.[5].

Conceptually, we start by considering how to describe damage incidence on a very large illuminated area. Because of the various material parameters and types of defects influencing damage initiation, a distribution of damage thresholds can be expected in contrast to a single definite threshold. For such a large area, some damage spots will occur even at low energy fluences and a single threshold is not very descriptive. The more recent practice of determining a damage probability curve corresponding to sampling an area with a number of small aperture tests is much more useful. However, as we will see below, the precise shape of such curves is highly dependent on the shape and area of the laser beam used in the test. A means of extrapolating to large areas with other beamshapes is given below.

We start with an overview of the problem of "extreme statistics", i.e. situations in which the overall strength is determined by the weakest point (some surface defect in our case). We propose[5] using the surface defect density underlying observed damage as a figure of merit and characteristic quantity. We observe experimentally that the cumulative damaging defect density typically varies rapidly with fluence, often as a power law or Weibull distribution. The Weibull plot analysis is of general use in engineering and is discussed in ref.[1]. A summary of scaling laws determined from computational simulations of fracture and breakdown for this type of phenomena is given in refs.[6-7]. The reader is also referred to descriptions of damage threshold area scaling[8] and the probabilistic analysis[9] of damage in KDP. We carry through below a generic calculation of damage incidence using intensity statistics from LLNL's NIF prototype Beamlet laser. We extrapolate typical small sample damage test data to NIF sized optics and compare the result to observed experience on Beamlet. This extrapolation gives encouraging results. Finally, we make several suggestions for gaining the necessary data and confidence to make reliable large area predictions of damage incidence.

3. FAILURE PROBABILITY APPROACH AND DAMAGE TESTS

We will characterize the distribution of damage inducing defects by the fluence at which they cause damage. We define P(S,F) to be the probability that a surface area S exposed to radiation of increasing fluence will damage at fluence F. The complementary probability U(S,F)=1-P(S,F) is then the probability to survive fluence F. Let the number of surface defects per unit area that produce damage at fluence between F and F+dF be defined as n(F)dF. Then, the incremental probability that the surface damages at F+dF given that it did not damage at F is the product of the probability of survival up to fluence F, U(S,F), times the probability of finding defects that damage in this interval, nSdF. That is,

$$P(S,F+dF)-P(S,F)= -(\,U(S,F+dF)-U(S,F)\,)= Sn(F)U(S,F)dF \tag{1}$$

or in differential form

$$\frac{dU(S,F)}{dF}=-S\,U(S,F)\,n(F) \tag{2}$$

The probability to survive at fluence F is seen to be given by

$$U(S,F)=\exp[-S\int_0^F n(F')\,dF']\,] \equiv \exp[-S\,c(F)] \tag{3}$$

Here $c(F) = \int^F n(F')\,dF'$ is the cumulative areal density of defects that cause damage at fluence less than F.

Several features are immediately clear. First, from Eq.(3), one sees that the area being tested appears in the exponent. The consistency of the area scaling in Eq.(3) was tested in ref.[5] by examining samples of 100, 500 and 900 test sites. It was shown that while the average damage fluence was accurately determined by the 100 site sample, the low fluence distribution varied systematically with sample size. It is this lowest fluence data that is most important for extrapolation to large areas.

From Eq.(3), if the survival probability is 50% at a given fluence and laser spot size, increasing the beam area by a factor of 10 reduces the survival to $(1/2)^{10} \approx 0.1\%$ at that fluence. One can immediately extrapolate the results for one area to another using the same rule. However, while correct, this gives an over pessimistic impression. That is, the 50% damage fluence may not decrease proportionately - the S-curve changes. In practice, the observed data have uncertainties including statistical sampling uncertainties and these uncertainties increase proportionately with the increased area making the experimental results less useful at the larger area. Related to this is the fact that low probability low damage fluence events at small area become most important for large areas, and these events, of necessity, have large statistical uncertainties. The damage vulnerability of the material is thus best described not by the damage probability derived from a particular test, but rather by the damage concentration c(F) which is characteristic of the particular surface. In summary, we relate the measured damage probability P (the S curve) to the concentration c through

$$P(F) = 1 - \exp[-c(F)\,S] \tag{4}$$

To proceed further analytically, we must specify the damage distribution function c(F). In many practical applications, a power law dependence of c on the "stress" factor (here fluence F) has proved useful in analyzing experimental data. This so-called Weibull distribution function) refs.[1-2,4-5] is of widespread use. A variation of this model was used in [4] to analyze area dependence of damage thresholds. We will use this Weibull distribution in the following since it generally fits LLNL data.

If one can reasonably fit an empirical model, such as the Weibull distribution, to the data and gain some confidence that it can be extrapolated to smaller fluences, then the model can be used to reliably estimate damage statistics for large areas. For example, suppose that one finds the cumulative defect distribution c(F) defined above to scale as the m^{th} power of fluence ($m \approx 2$-22 in LLNL data). Then the 50% fluence for an area 10 times larger than that of the original experiment will be reduced by a factor of $10^{1/m}$ which is a reduction of only about 20% for m=10. The fact that both statements (survival at original fluence is near zero, 50% fluence drops by 20%) can be true is a reflection of the fact that the S-curve of damage probability becomes sharper for larger areas.

We carry out two types of damage tests. The Automatic Damage Tester (ADT) (see Sheehan, et al, this proceedings) increases the fluence until a site damages (R/1 test). Typically, a beam with diameter on the order of 1mm is used and the individual N sites are well separated. A cumulative damage probability curve (S-curve) is found from the ratio of the number of sites that damage below fluence F to the total number of sites N. Our Large Area Tester (LAT) (see Schwartz, et al, this proceedings) raster scans an area at constant fluence leading to an area density of damage sites. A beam with diameter on the order of 1 mm is used for the raster scan. Since the beam is stepped a fraction of a beam diameter in making the scan, there is beam overlap. As noted above, the irradiance distributions in these two test scenarios are important in understanding the test results. With the LAT, we scan relatively large areas (e.g. 20 cm^2). This necessitates lower test fluences than for ADT and only a few values of fluence.

ADT Damage test results usually are presented in terms of the cumulative damage S-curve. The actual observations from which the S-curve is derived typically show considerable statistical scatter. We show in Fig.(1) the 1 mm^2 damage probability distributions derived from several samples of fused silica. Because of the small beam size, appreciable damage probability occurs at much higher fluences than those appropriate for a large optic. It is, of course, precisely the low fluence low probability values that are needed for extrapolation to large areas. Fig.(2) shows a Weibull plot (ln(-ln(1-P)) vs. ln F) for this data. Overall, this data fits the Weibull form quite well with a power (Weibull exponent) of 10-14. Once the Weibull fit is made, one can calculate the effective area (see Sec. III) and derive the damage concentration. Further discussion of Weibull analysis of ADT test results is given in ref.[5].

LAT test results are usually presented in terms of number of damage sites within some scanned area. It is very natural to report these as a damage concentration (once the area correction for irradiance distribution is made). The principle difficulty in analyzing these results comes about from the complicated irradiance pattern used in scanning. Since damage incidence depends on the peak fluence seen at a point, it is necessary to calculate the effective area of a flat beam with the same maximum fluence. (see below). This can be done once the Weibull exponent is determined. Typical LAT raw and area corrected data are shown in Figs.(3-4).

4. IMPORTANCE OF DAMAGE TEST BEAMSHAPE AND SIZE

In the formulation above, S refers to the "illuminated area", but one has to be careful about what this means for a nonuniform beam. In particular, we have observed that damage probability for high quality samples typically depends on a high power of the fluence, e.g. m=12. If the illuminating beam is Gaussian shaped, for example, the effective source for initiating damage depends on the mth power of this Gaussian which is much more strongly peaked than the Gaussian. Thus, an effectively smaller area is illuminated at the peak fluence. In general, one should replace S c(F) in Eq.(3) by the integral $\int c\, dx\, dy = c(F_0)S_{eff}$, where F_0 is the peak fluence and S_{eff} is an effective illuminated area.. Thus for a Gaussian beam with $F = F_0 \exp(-(r/\sigma)^2)$, one finds the appropriate area to use is $S_{eff} = \pi\sigma^2/m$ in order to find the "intrinsic" damaging defect density needed to estimate results for a flat beam. Thus, an effective area, determined jointly by the beamshape and the defect density must be calculated to normalize the defect density found from experimental observations.

In a typical small beam area damage test, measurable damage is generally found only at fluences greater than operational fluences for large area optics. The Weibull distribution (once ascertained correct) can be used to scale the results to lower fluences.

As an example, consider recent ADT tests (7.5 ns pulse) on a Zirconia polished sample. The beam $1/e^2$ radius was 1 mm so the effective area is about 0.1 mm^2. The experimentally determined cumulative densities at 36 J/cm^2 were found to be $c_1(36\ J/cm^{-2}) = 411\ cm^{-2}$ with m=17 and $c_2(36\ J/cm^2) = 376\ cm^{-2}$ with m=14 where the subscripts refer to side 1 and side 2. The NIF redline fluence for 7.5 ns pulses is 20.6 J/cm^2. At this fluence, the damaging defect density is expected to be given by $c(36)\ (20.6/36)^m$ which gives $c_1 = 0.03\ cm^{-2}$ and $c_2 = 0.15\ cm^{-2}$. For a NIF size optic of 1600 cm^2 area, we thus expect about 48 damage sites on side 1 and 240 sites on side 2 at the redline fluence. The difference is due to the different values of m (see Fig.(9)). The low values reflect the high damage resistance quality of the sample. The extrapolated differences for the large area emphasize the utility of using the exponent m as a figure of merit, all else being equal. In general, one can characterize the curve by its slope and value on a log-log plot. At the lower operational fluences, very few damage sites would be expected on a large optic made of this material.

For the LAT raster scan, one has to evaluate $\int c\ dx\ dy = c(F_0) S_{eff}$ using $c(F) = c_0\ F^m(x,y)$ where F(x,y) is the distribution of peak fluence over the scanned area. Evaluating this integral for a Gaussian scanning beam and choosing the scan step so beams overlap at a fraction f of the peak intensity, we find that $S_{eff} / S_{scan} = (\pi/4)\ [\mathrm{erf}(arg)/arg]^2$ where $arg = \sqrt{(m\ \ln(1/f))}$

The analysis presented here allows comparison between different types of tests, eg. the ADT tests shown above and large area raster scans (LAT) in which case tens of cm^2 are scanned at constant fluence and resulting damage sites counted. Fig.(5) compares the derived damage density for ADT and LAT tests for silica with various polishing processes. It is seen that the cumulative damaging defect densities found cover a range spanning six orders of magnitude and results of the two types of test are consistent.

5. EXTRAPOLATION TO LARGE AREA OPTIC

Above, we considered the probability of finding a single damage site within an area S. For a very large area, the practical issue is the damage density or area per damage site given some fluence distribution. Thus, the goal of small sample damage tests is to predict the damage density on a very large sample. The observed results presented above suggest the following approach.

Typical tests yield damage density for an effective flattop beam once the effective area correction is made from the beamshape and the slope of the Weibull curve. For a sufficiently large population of sites, especially at the lower fluences, one can use the power law fit to extrapolate to the lowest fluences of operational interest. However, large area high power beams never have uniform fluence, but rather some distribution (Fig.(6)). As with the small beam tests, one again has to account for the fluence distribution. For example, for a beam with normal, i.e. Gaussian beam statistics, one can make a simple analytic estimate of the effect of the fluence distribution. The expectation value of the exponent in Eq.(3) can be found by expanding the integrand around the mean fluence value. If the average fluence is F_0 and the 1/e width of the fluence distribution is σ, then one finds
$P(F_0) = 1 - \exp(-S < c(F_0) >)$, where

$$< c(F_0) > \ \approx c(F_0) \sqrt{\frac{4\,b^2}{4\,b^2 + 2\,m}}\ Exp\left[\frac{m^2}{4\,b^2 + 2\,m}\right] \tag{5}$$

Here, $P(F_0)$ is the expected damage probability as a function of the mean fluence, $P_0 = 1 - \exp(-S\ c(F_0))$ is the damage probability obtained for a perfect flattop beam at fluence F_0, $b = F_0/\sigma$, and m is the slope of the Weibull curve. This is a good approximation provided that

$$b = F_0/\sigma >> m^{1/3} \tag{6}$$

i.e. for a sufficiently small variance (e.g. for m=12, σ/F_0 should be less than 0.4). Here c(F) is the cumulative damage density as before and <c> refers to the expectation value. This condition is satisfied for the distribution given in Fig.(6). Eq.(5) gives insight into the effect of fluence deviations. Eq.(5) is approximate; in the case where m does not satisfy Eq.(6), it is possible to simply find $P(F_0)$ by numerical integration using the exact expression

$$<c(F_0)> = \int_0^\infty c(F)\, f(F)\, dF \tag{7}$$

where f(F) is the fluence distribution of the large beam and the cumulative defect density c(F) is obtained from the Weibull fit of the small beam test data.

Note that the factor multiplying $c(F_0)$ on the rhs of Eq.(4) gives the increase in expected damage density due to the fact that the illuminating fluence is not fixed, but has a distribution. This "damage enhancement factor" (DEF) can be used as a figure of merit in comparing the damage effects of beams with structure or random fluctuations. In the case calculated below, the DEF=1.14, i.e. the damage density is expected to be 14% higher than for a flat beam at the average fluence.

We present here "generic" type calculations to show the orders of magnitude involved. Fig. (6) shows a typical experimental fluence distribution at a large lens on the LLNL Beamlet laser. The mean 3ω fluence is 5.3 J/cm^2 and the full 1/e width is about 30% . Fig.(7) shows the result of extrapolating the area corrected small area LAT results for a typical high quality lens. The test results have been adjusted for the Beamlet fluence distribution and $\sqrt{\tau}$ scaling of fluence assumed. On the same plot, we show the observed damage density after the 38 shot frequency tripling campaign on Beamlet. The expected and observed densities agree quite well. The curve of expected damage assumed that beam statistics are the same shot to shot. It is known that this is not so. If intensity fluctuations (hot spots) move around completely randomly from shot to shot, the expected damage density would increase another factor of about 2. The tripler campaign was chosen as an example since its relatively low beam fluences offer the best opportunity to establish the usefulness of the analysis proposed here. On higher fluence series, complications due to system effects (interactions of different optics via beam modulations and/or contamination) can complicate the interpretation of damage incidence.

6. CONCLUSIONS

Reliable probabilistic estimates of damage for large optics can be based on damage studies of smaller samples. Conceptually, it is important to focus attention not on the probability of damage which depends on the size of the area tested, but, rather, on the areal density of sites that damage at a given fluence. This density is characteristic of a homogenous material and can be extrapolated, assuming homogeneity, to find the damage density on an infinite area sample. The practical requirement for such extrapolation is adequate knowledge of the low fluence damaging defect density c(F). The following recommendations and questions are suggested from the above.

Previous treatments of laser damage tried to establish a threshold for a particular sample. The statistical nature of damage has been recognized by introducing the threshold distribution (S-curve) for a given sample. In practical terms, the relevant question is what is the probability for a given tolerable damage density. Reliable estimates of this probability will depend on accurate knowledge of the damaging defect densities described above. The tolerable level of damage is likely to be different for different materials and operating environment. For example, 1ω spatial filter lenses with one side in vacuum and the other side in air are subject to large mechanical loading. Since the more vulnerable 3ω optics are in vacuum and at the end of the chain, the level of tolerable damage can be quite different.

Reliable probabilistic estimates of damage levels will require not only extrapolating small area damage observations to larger areas, but also knowledge of how initial pinpoint damage grows with subsequent shots. This knowledge can then be combined with a detailed model of temporal and spatial fluctuations expected in the NIF pulse to produce realistic estimates of damage related beam obscuration. Of course, one can never be absolutely sure there are no "extremely rare" damaging defects without full aperture scanning.

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Figures

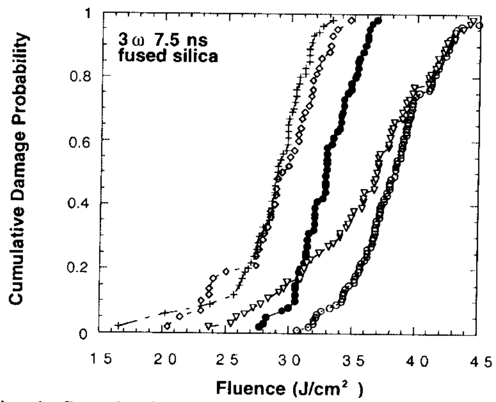


Fig. 1: Standard S-curves for silica samples finished with three different polishing processes. τ=7.5 ns.

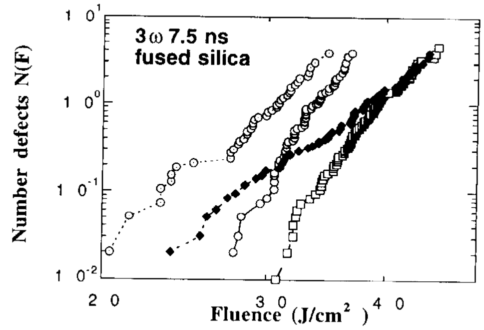


Fig. 2: Cumulative damaging defect distribution functions found from the data in Fig.(3).

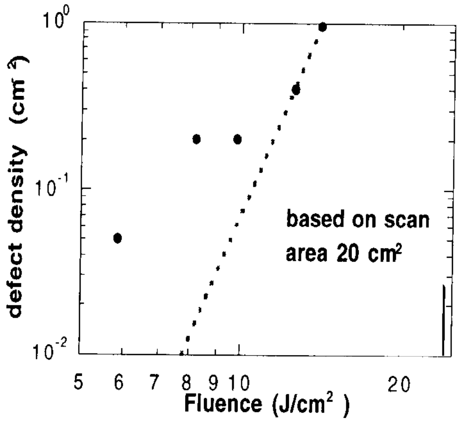


Fig. 3: LAT raster scan of large areas at a few fluences yields surface density of damage sites.

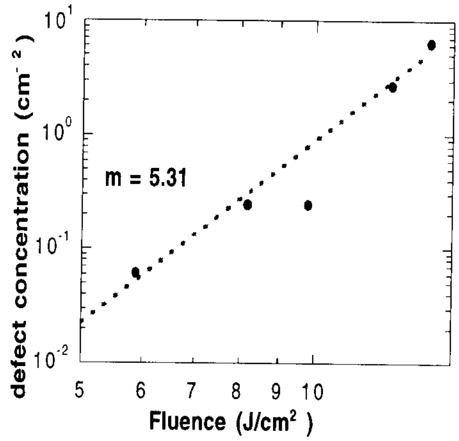
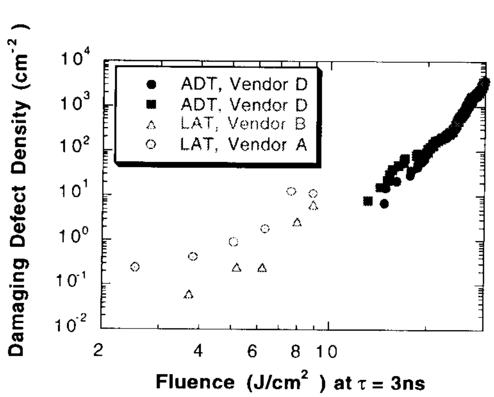


Fig.4: Analysis (effective area correction) allows expressing LAT results as density expected for flattop beam.



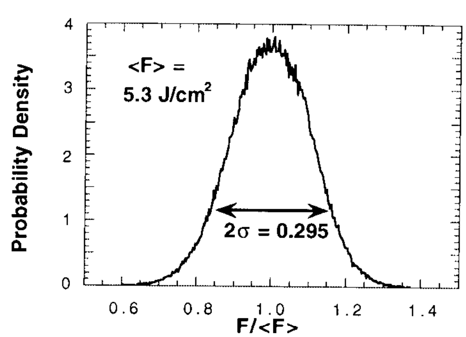


Fig. 6: Typical Beamlet intensity distribution (courtesy of P. Wegner) for medium damage

Fig.5: Damage densities derived for fused silica from small area (ADT) and large area (LAT) tests are consistent. Note that density increase of about five orders of magnitude corresponds to a fluence increase of about one order of magnitude.

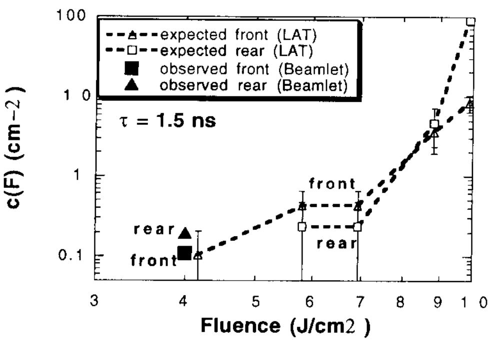


Fig. 7 Expected damage concentration derived from LAT offline test results for lens compared with experience on Beamlet 38 shot tripler campagin. Expected damage uses peak series fluence; detailed accounting for shot to shot beam structure could change calculated values by up to a factor of 2.

threshold campaign with average fluence of 5.3 J/cm^2